HIF (Heavy Ion Fusion) Gas Desorption Issues*

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With contributions from

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Workshop on Beam-Induced Pressure Rise in Rings
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OUTLINE

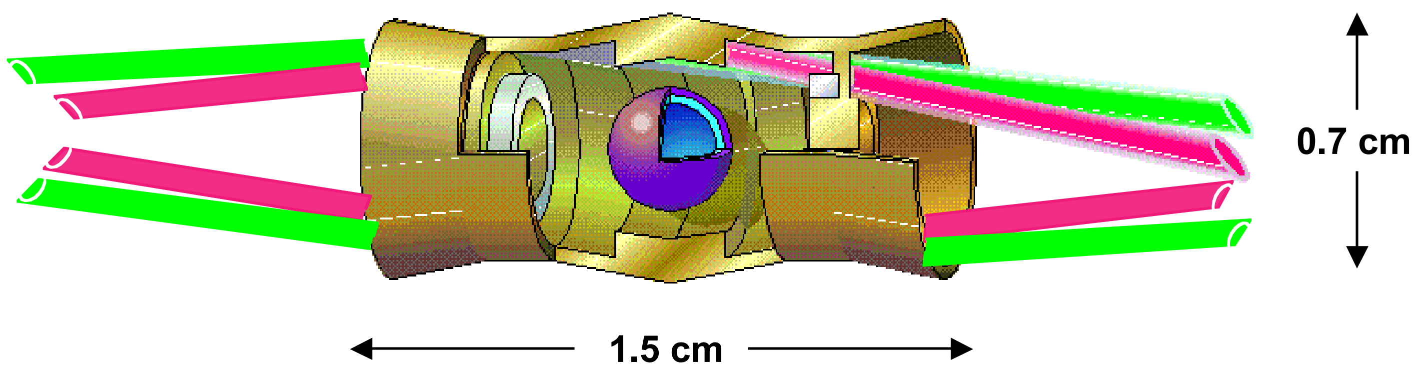
- Introduction to Heavy Ion Fusion (HIF)
  - Recent Robust Point Design (RPD) – a self-consistent, detailed, and conservative HIF power plant design
- Why are we concerned about pressure rise in a linac?
- Pressure rise issues at several Hz
- Measurements of gas desorption & electron emission
- Hypotheses on sources of gas and electrons

Target Requirements establish accelerator requirements for power plant driver

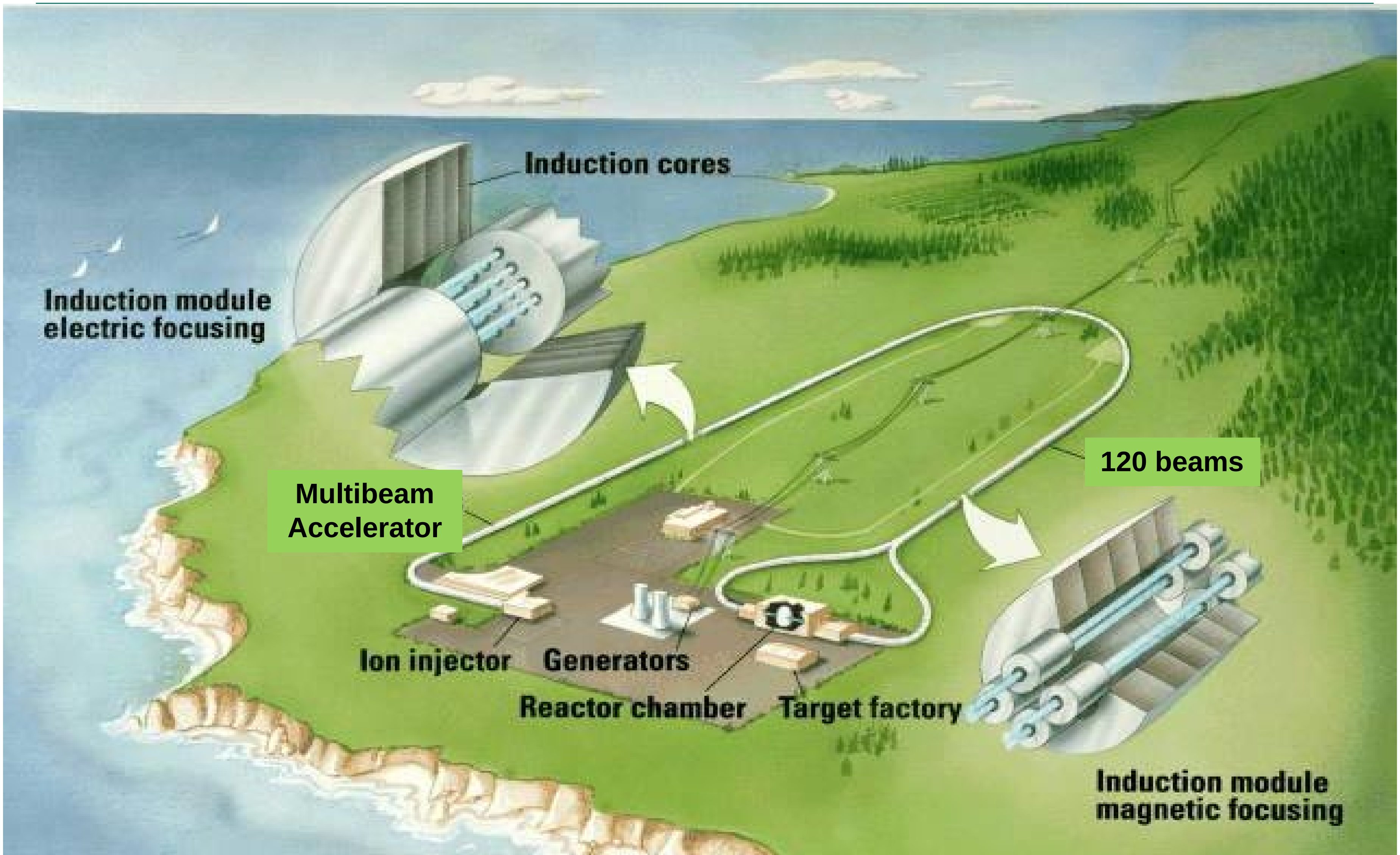
3 - 7 MJ x ~ 10 ns ⇒ *~ 500 Terawatts*

Ion Range: 0.02 - 0.2 g/cm^2 ⇒ *1- 10 GeV*

Beam charge (3-7 MJ/1-4 GeV) ⇒ few mCoul



Artist s Conception of an HIF Power Plant on a few km^2 site

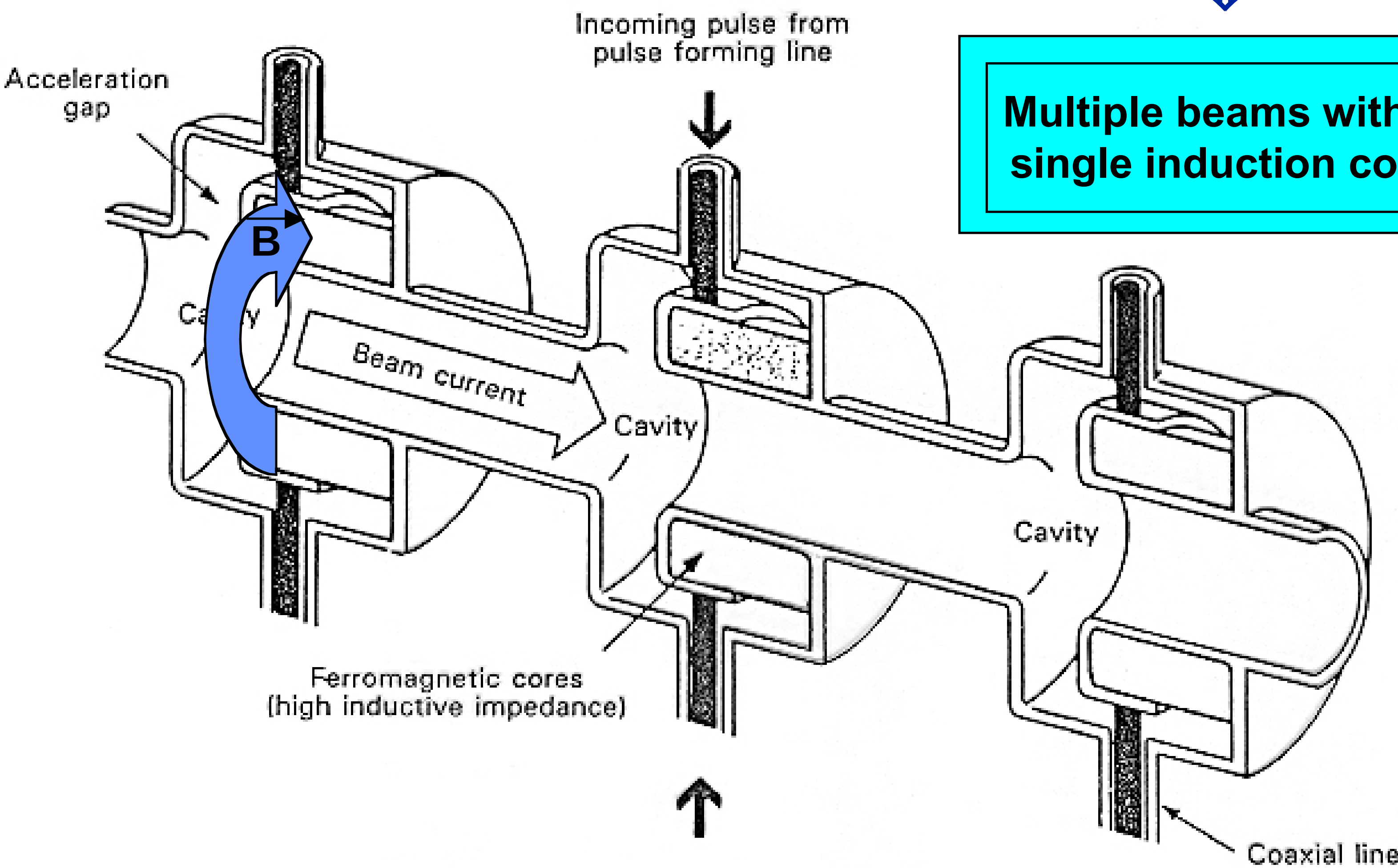


Induction Acceleration is used for efficiency

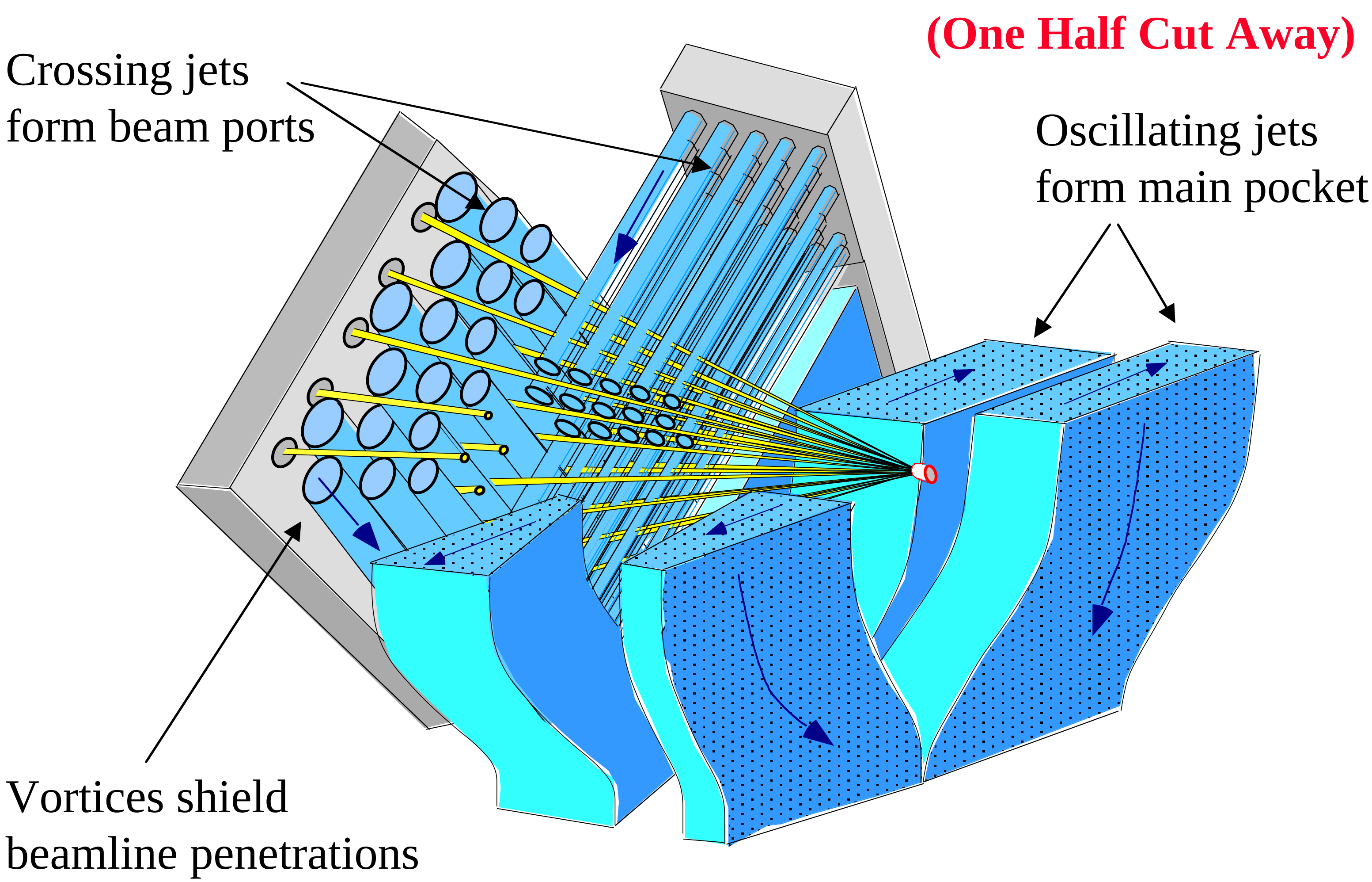
Efficiency increases as current increases

$\Downarrow$

Multiple beams within single induction core

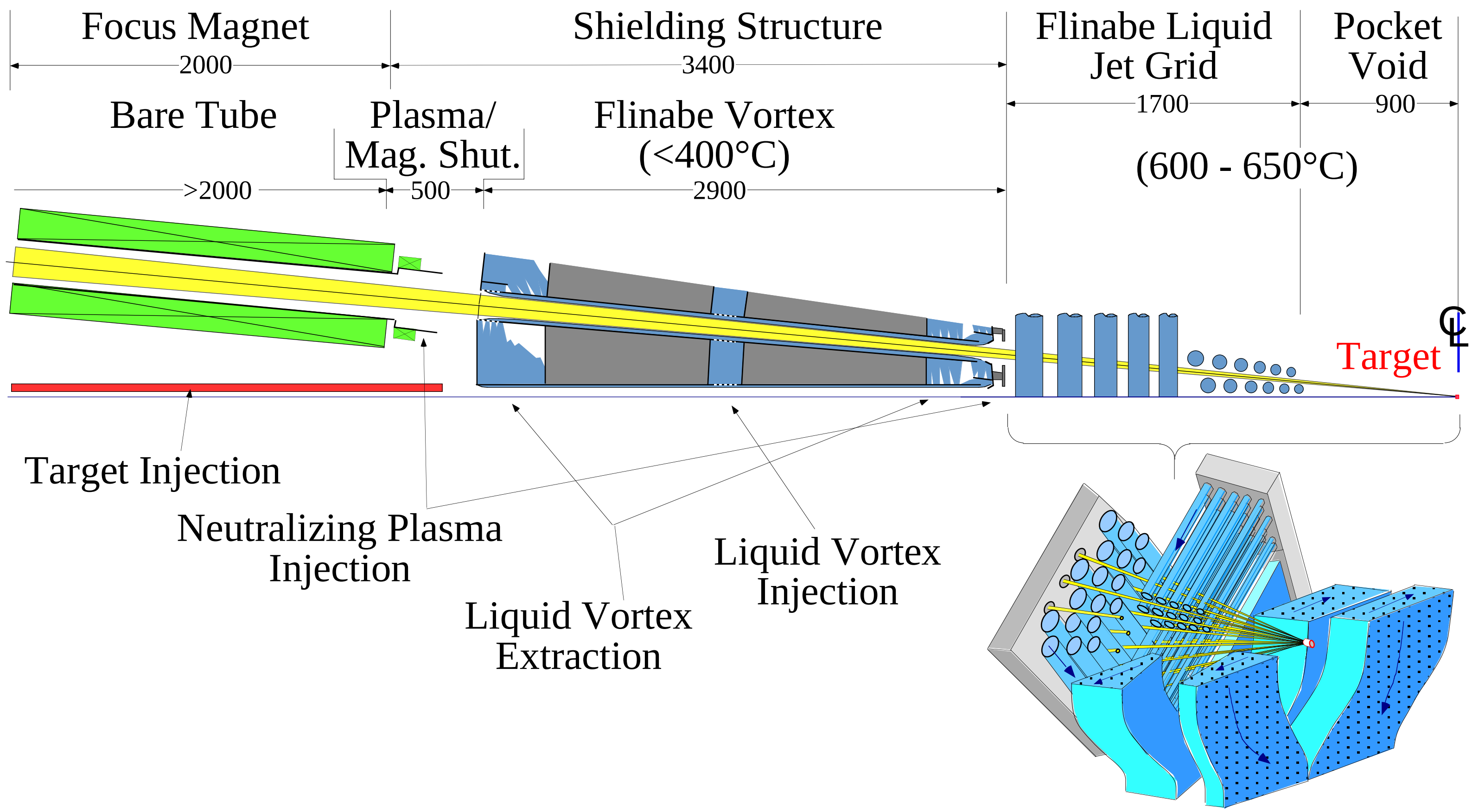


The First Wall Protected by Neutron-thick Molten Salt FLiBe,
FLiBe is a low Z salt ⇒ low activation ⇒ Green fusion energy



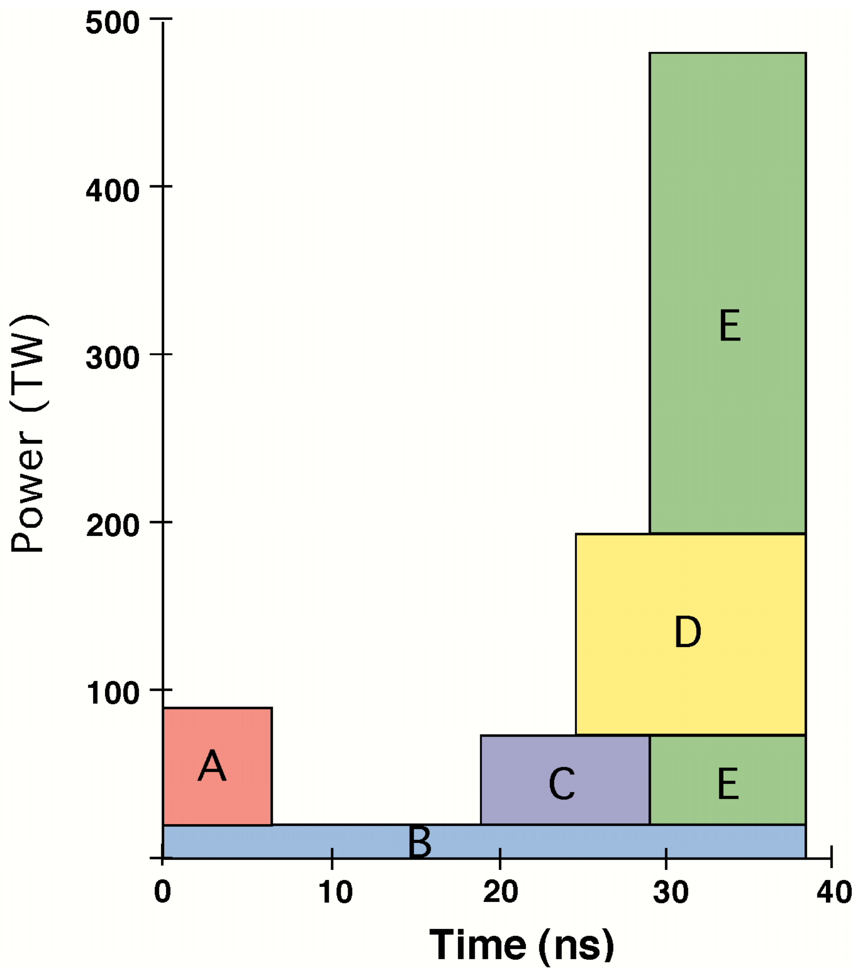
But vapor density ~ 10^{13} cm^{-3} too high for accelerator

The Robust Point Design beam line —pumps and blocks chamber vapor from accelerator



Schematic Liquid Jet Geometry

Building block pulse shape —illustrative of conservative approach in Robust Point Design



Beam and Pulse Shape Requirements

Block	No. of Beams	Power, TW	Pulse width, ns	Energy, MJ
A (Foot)	16	70	6.5	0.46
B (Foot)	16	20	38.3	0.77
C (Foot)	16	53	10.1	0.54
D (Main)	24	120	13.7	1.64
E (Main)	48	388	9.3	3.61

48 foot pulse beams:
T = 3.3 GeV, E_F = 1.76 MJ

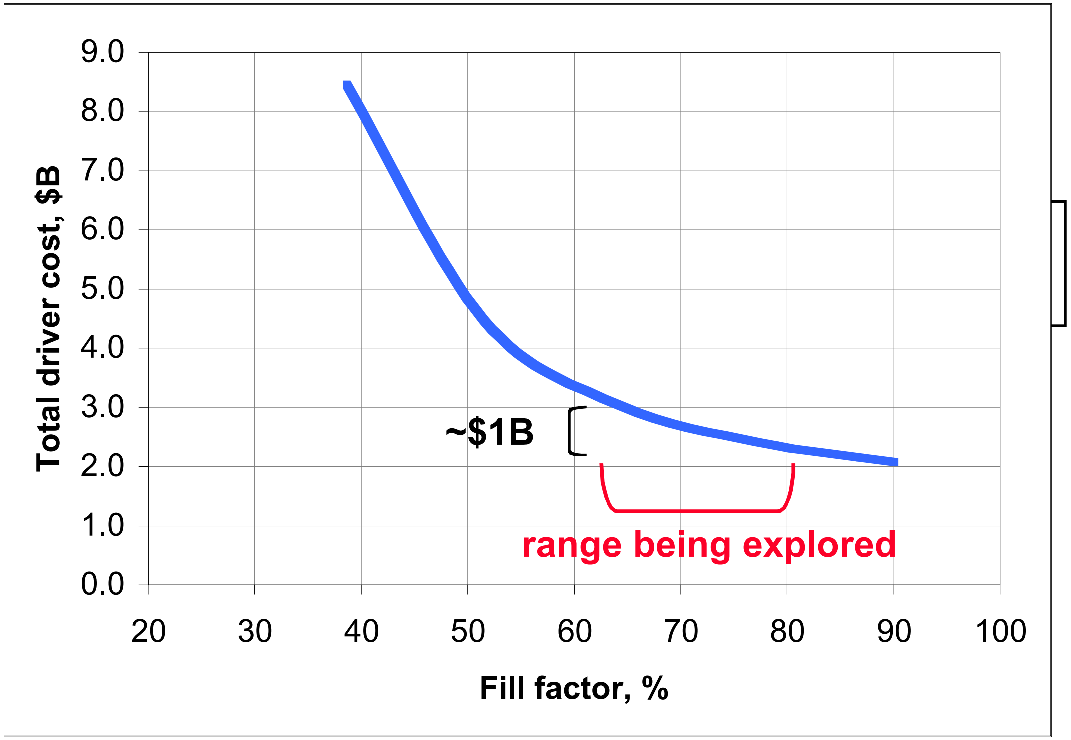
72 main pulse beams:
T = 4.0 GeV, E_M = 5.25 MJ

120 total beams:
E_D = 7.0 MJ

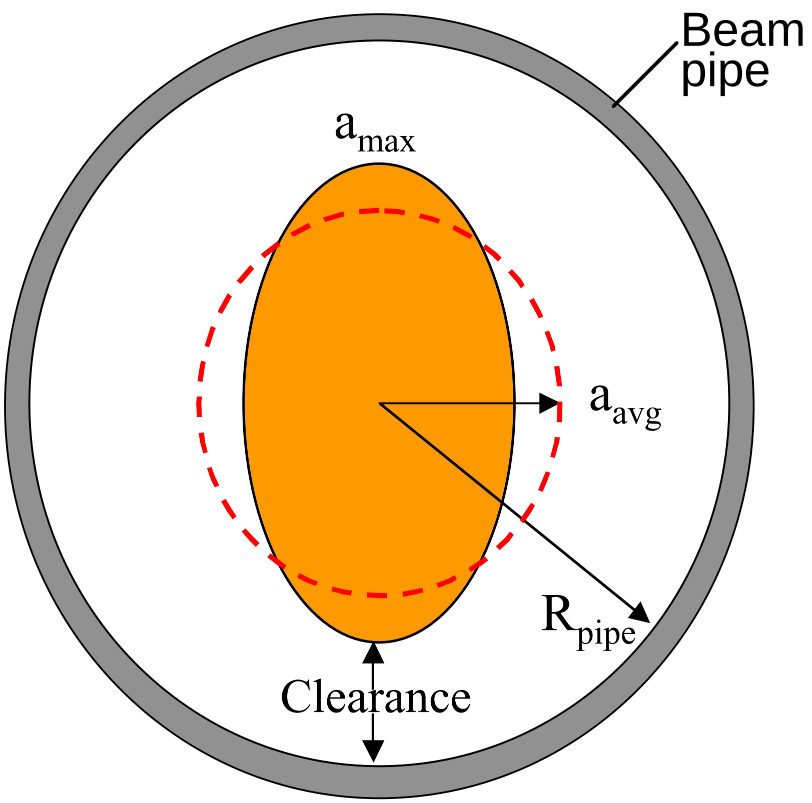
System studies show that driver cost reduced at high fill factor [fill factor may be limited by beam-induced desorption]

Electron Cloud Effects (ECE) may also limit HIF Fill factor

IBEAM results:



Fill factor = a_{max}/R_{pipe}



(fixed number of beams, initial pulse length, and quadrupole field strength)

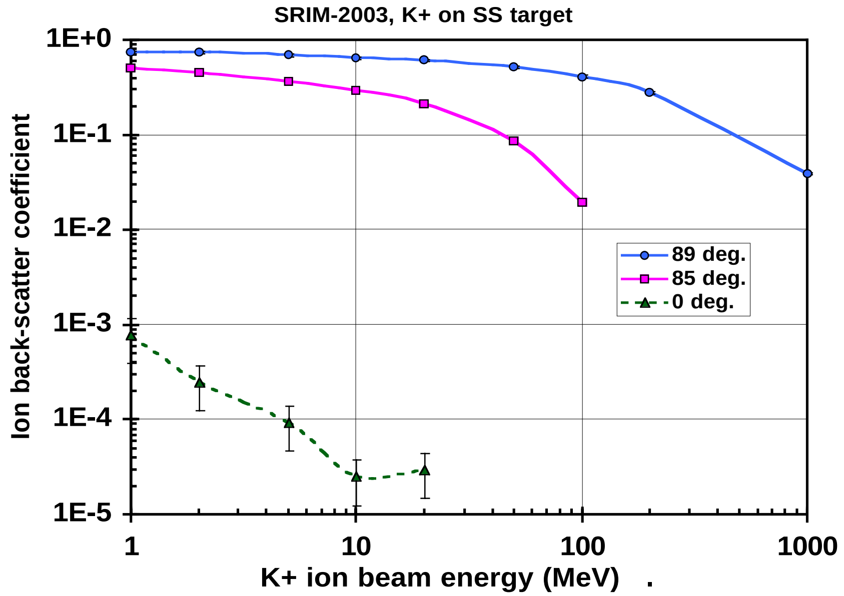
Gas desorption (or ECE) may be an issue in HIF linacs

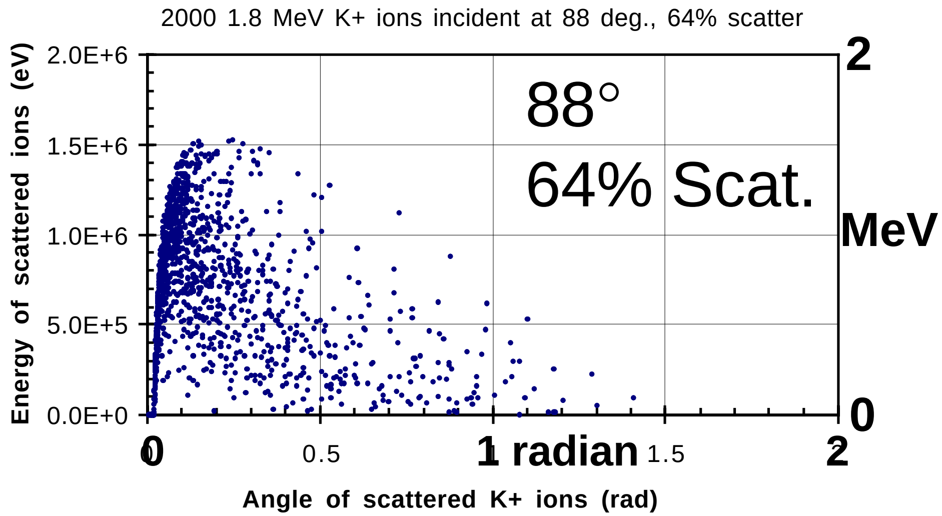
- **Economic mandate to maximally fill beam pipe**
- **Linac with high line charge density (Beam potential > 1 kV) {ionized gas ions expelled to wall, Γ_{og} ~ 10 }**
- **Induction accelerator – pulse duration up to ~20 μs at injection, down to ~0.2 μs at higher energy [Time for desorbed gas to reach beam], ~5 Hz rep. rate [time to pump desorbed gas?], multiple beams in parallel, frequent acceleration gaps, large neutral desorption coefficients at pipe wall (~10^3 - 10^4 in present HIF-VNL, CERN, and GSI heavy-ion accelerators)**
- **Heavy-ions – stripping cross sections $\sigma \propto E^{-0.5}$, $\sigma v \propto E^0$; don't win at high energy like proton accelerator where $\sigma \propto E^{-1}$**
- **Large fraction of length occupied by quadrupoles (>50% at injector end)**

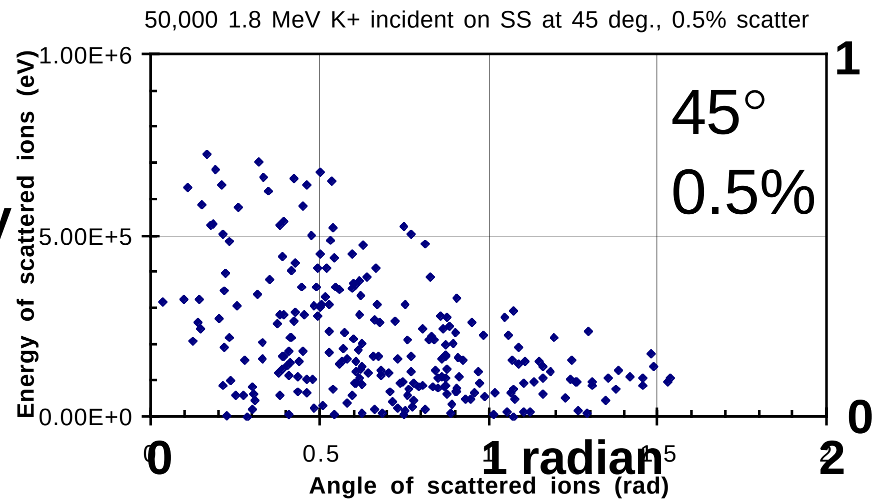
Heavy ions may hit wall multiple times, increasing desorption

TRIM Monte Carlo Code predicts

- 60-70% scatter at 88-89°
- 0.05-0.5% scatter at 0-45°
  - ⇒ Beam scrapers effective
- Spread in angle ~0.2 rad.
- Issues
  - Spreads ion loss azimuthally
  - Causes electron emission
  - Scattering decreases slowly with energy near grazing incidence.







Gas buildup can limit peak beam current in rapidly pulsed accelerator

$$\pi r_w^2 \frac{dn_o}{dt} = \underbrace{\boxed{n_b n_o \sigma_i v_b \pi a_b^2 \Gamma_{og}}}_{\text{Ionize gas - } \Gamma_{og}=10} + \underbrace{\boxed{n_b n_o \sigma_x v_b \pi a_b^2 \Gamma_{ob}}}_{\text{Charge-exchange loss of beam}}$$

$$+ \underbrace{\boxed{n_b v_b \pi a_b^2 f_{halo} \Gamma_{ob}}}_{\text{Halo loss}} - \underbrace{\boxed{2\pi r_w f_{wp} n_o \frac{v_o}{4}}}_{\text{Pumping: } f_{wp} = \text{ fraction of wall that pumps}}$$

$$I_b = q n_b v_b \pi a_b^2$$

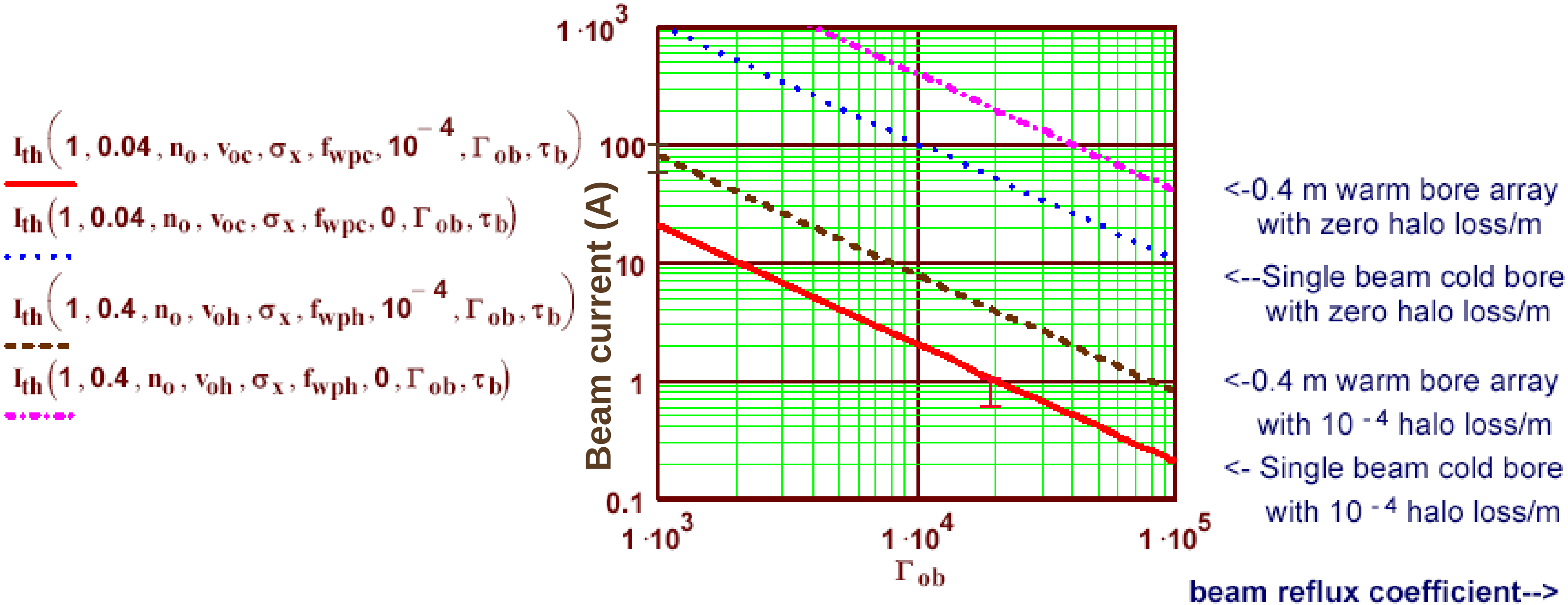
$n_{b,o}$ {$v_{b,o}$}beam, neutral density (m^{-3}) {velocity (m/s)}
σ_i cross section for beam ionization of gas
σ_x charge-exchange of beam on gas
a_b {r_w }beam radius; {wall radius}
$\Gamma_{og,ob}$ desorption coefficient for expelled ion (from gas), beam ion.
f_{halo}, f_{wp} fraction beam lost per m, fraction wall open to cryo-pump.

Solve for I_b, convert to peak current with inverse duty cycle at 5 Hz.

$$\hat{I}_b = \left(\frac{0.5 q e \pi r_w f_{wp} n_o v_o}{\underbrace{n_0 \sigma_i \Gamma_{og}}_{\text{small}} + n_0 \sigma_x \Gamma_{ob} + f_{halo} \Gamma_{ob}} \right) \left(\frac{0.2}{\tau_b(s)} \right)$$

Where
τ_b = beam duration (≤20 μs)

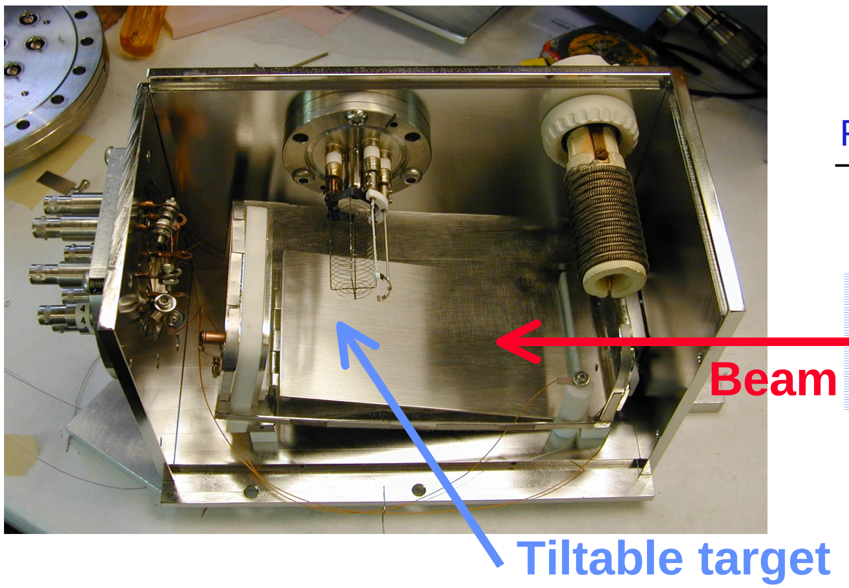
Beam desorption coefficients necessary for HIF:

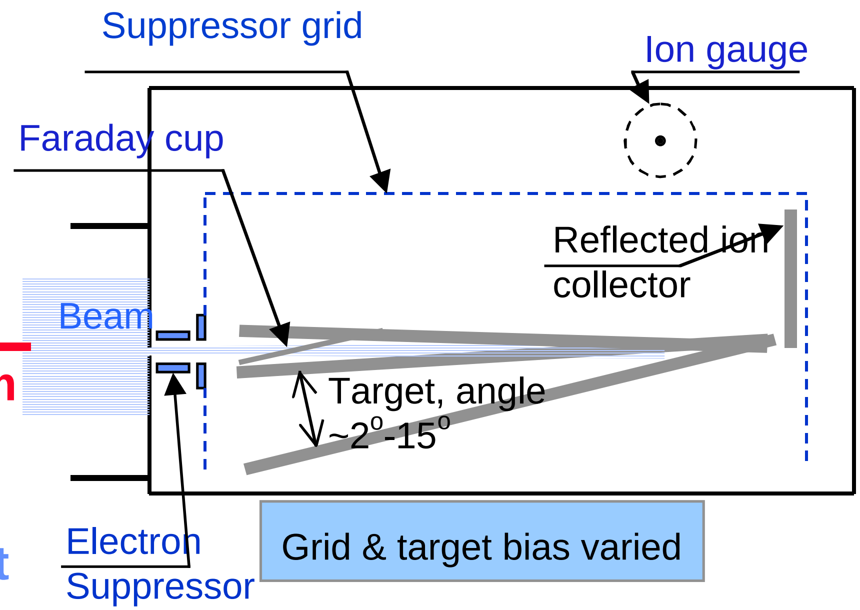


- HIF cold bore: each beam pumped by its own beam tube, limit applies to each beam [I need $\Gamma_{ob} < 2 \times 10^4$ for $I_b \geq 1$ A].
- Warm bore: pumping between quad. magnets, limit applies to sum of beam currents in array [I need $\Gamma_{ob} < 10^3$ for $I_b \geq 100$ A].
- Both limits relaxed if beam halo loss less than 10^{-4}/m

Measure electron emission and gas desorption from 1 MeV K^+ beam impact on target

Gas, electron source diagnostic (**GESD)**



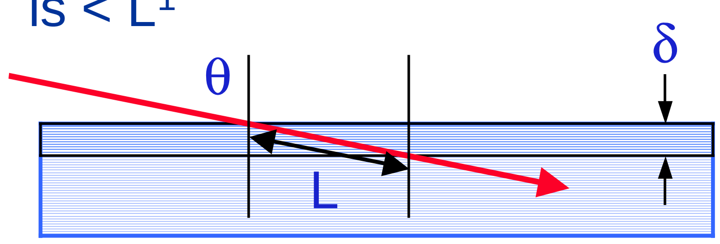


- Measure coefficient of electron and gas emission per incident K^+ ion.
- Calibrates beam loss from electron currents to flush wall electrodes.
- Evaluate mitigation techniques: baking, cleaning, surface treatment…

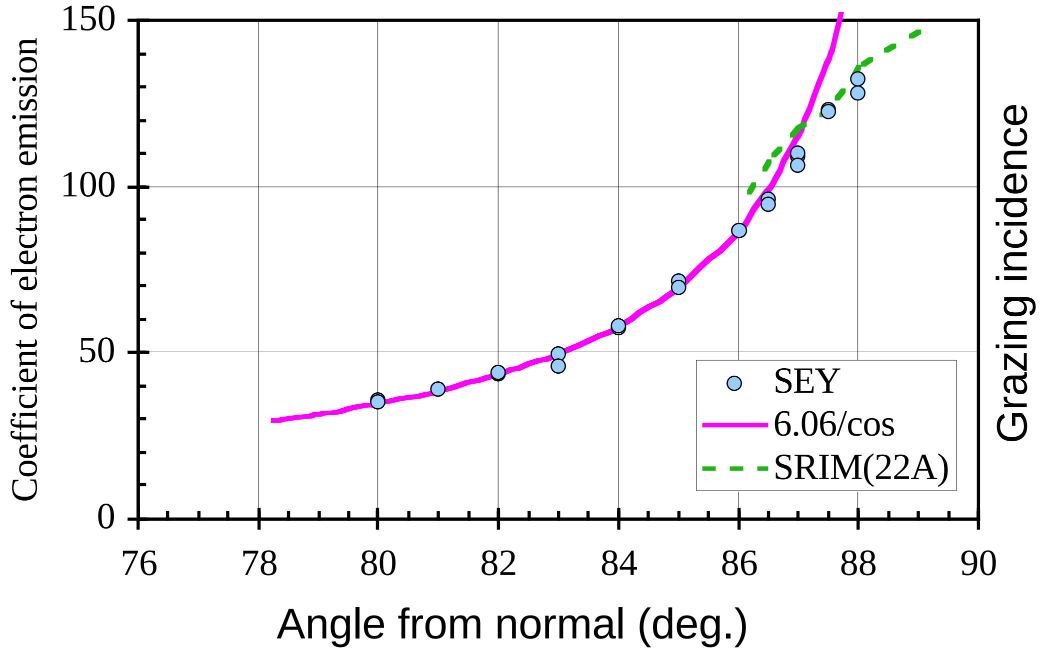
GESD secondary electron yield (SEY) varies with $\cos(\theta)^{-1}$

- Simple model gives $\cos(\theta)^{-1}$
  - Delta electrons pulled from material by beam ions (dE/dx)
  - Electrons from depth $> \delta$ ($\delta\sim$ few nm) cannot leave surface
  - Ion path length in depth δ is L.

    $L = \delta / \cos(\theta)$
- Results depart from this near grazing incidence where the distance for nuclear scattering is < L[1]

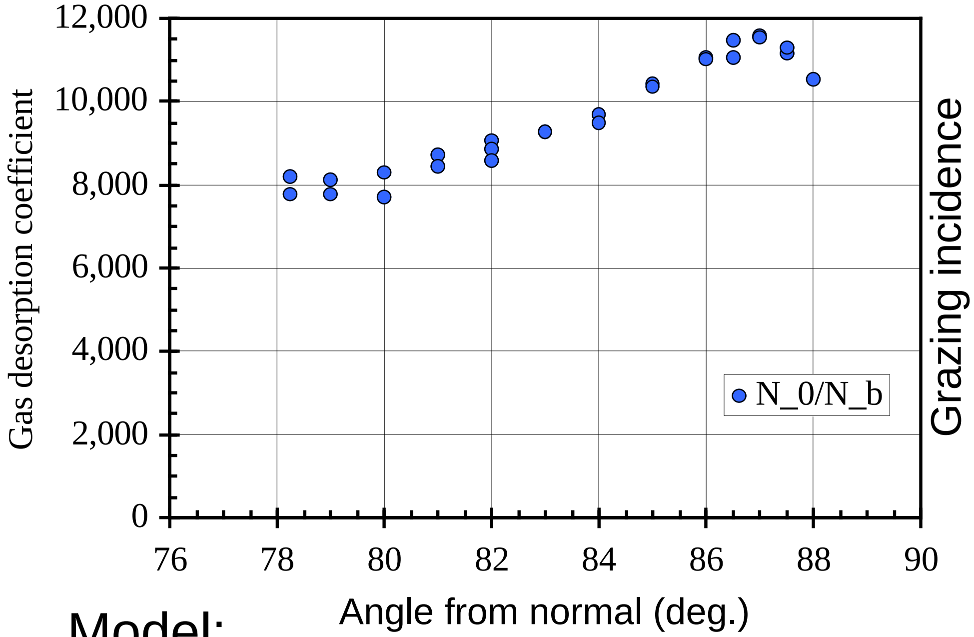


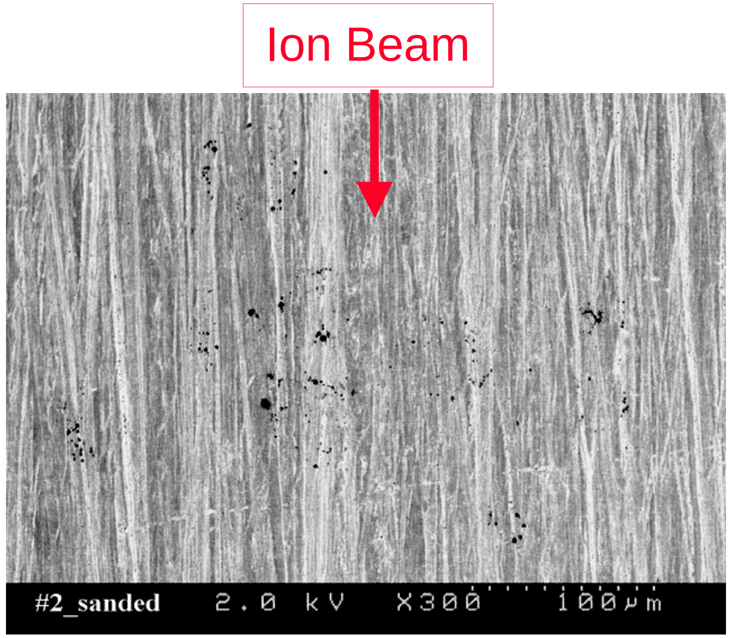
$L = \delta / \cos(\theta)$



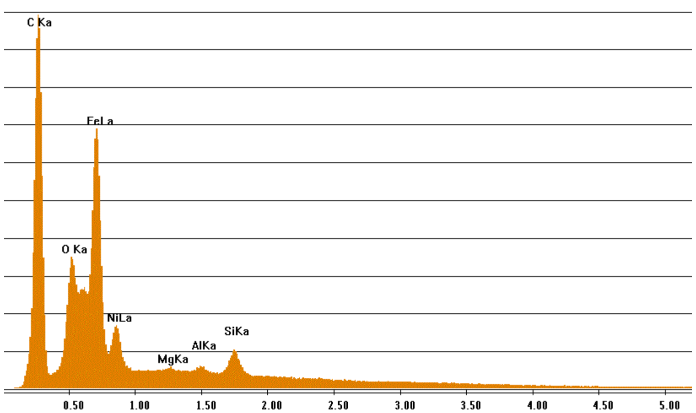
1. P. Thieberger, A. L. Hanson, D. B. Steski, et al., Phys. Rev. A 61, 42901 (2000).

GESD gas desorption coefficient varies more slowly than $\cos(\theta)^{-1}$ ∴ not mainly from adsorbed gas layers





Label A: Molvik, 304 stainless, sample 2 - sanded, 1.0u dia surface deposit, 6KV



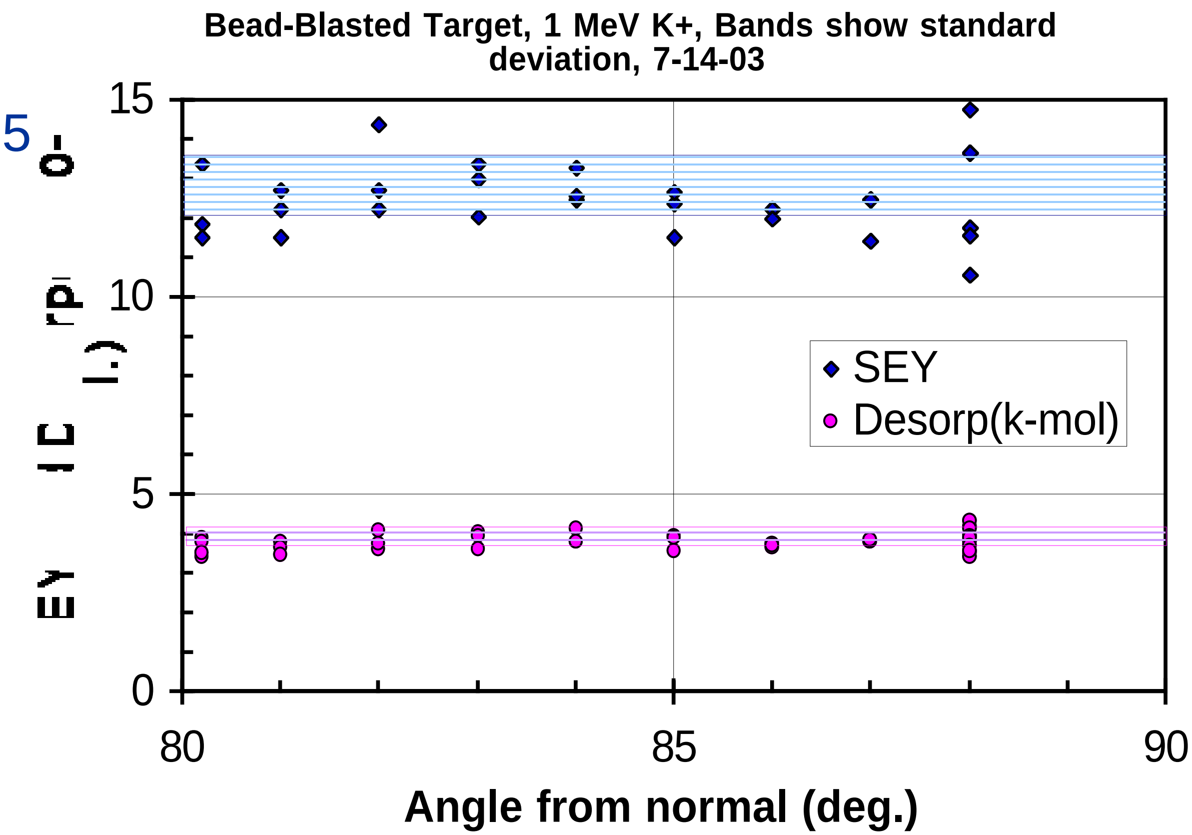
Model:

- Gas desorption results from electronic sputtering of gas film on surface plus dust and oxides on surface and impurities near surface.
- Film would result in $\cos(\theta)^{-1}$ [not seen so other sources dominate.]

Similar results reported for 800 MeV Pb on SS at CERN
E. Mahner, et al., PRST-AB 6, 013201 (2003)

Is SEY ∝ 1/cos because electrons originate in beam-ionized gas? —No

- Gas expands ~2-3 mm/µs, so fills 3 mm high beam in fraction of 5 µs FWHM.
- If electrons from beam-impact on gas, electron production ∝ 1/cos
- SEY=13 & 1/cos ⇒ Electrons are from ion impact on surface at an average angle of 60° from normal.
- At 60 °, ion reflection is reduced to ~3%.

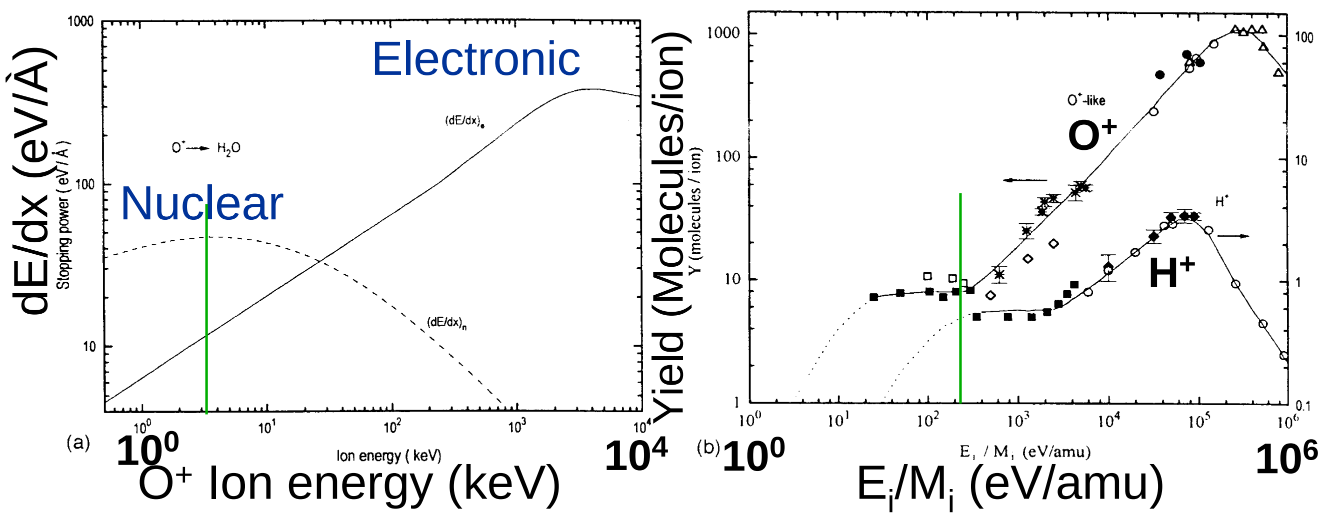


Mitigation technique: rough surface reduces SEY x10, gas desorption x2, but harder to beam scrub.

Electronic sputtering can account for larger gas yields than physical sputtering

From TRIM Code:

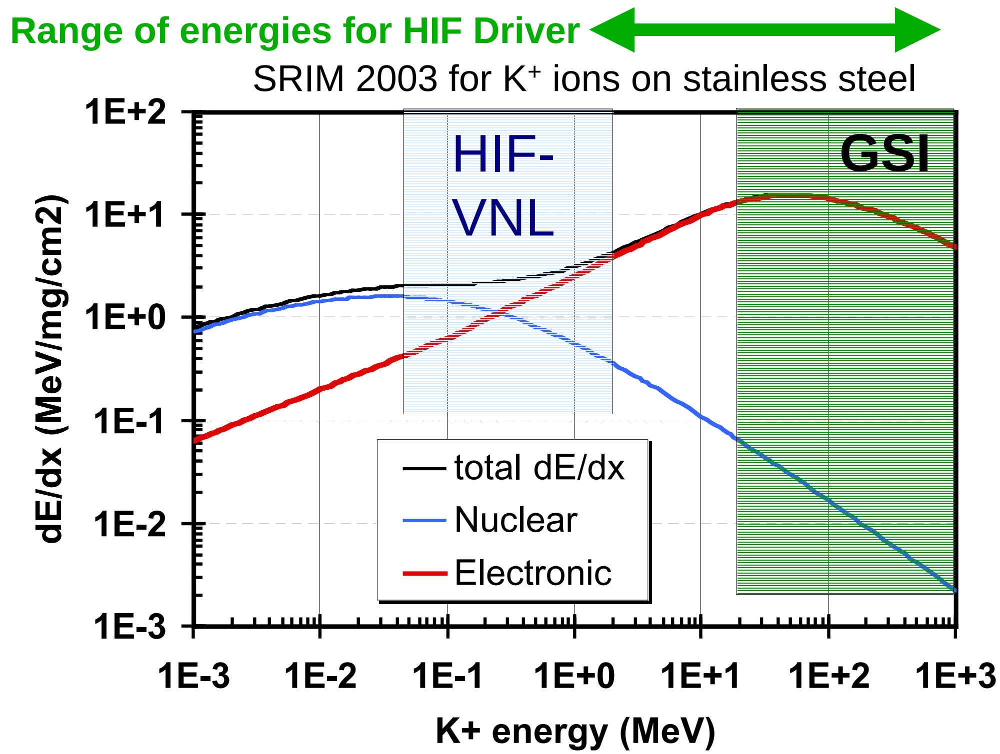
Measured sputtering yield for H^+ and O^+ incident on H_20 at ≤80K



- Nuclear-elastic (knock-on) collisions ⇒ physical sputtering
- Electronic component ⇒ electronic sputtering.
- Sputtering from ion and electron bombardment of frozen gas is believed to be the source of tenuous atmospheres on moons of outer planets.*
- Electronic sputtering applies to insulators, not metals. But observed gases (H, C, O compounds) would have been insulators on surface.

* R. E. Johnson, "Sputtering of ices in the outer solar system" RMP 68, 305 (1996).

Electronic sputtering model is being tested by HIF-VNL



GSI Collaboration offers opportunity to test model over wide energy range, including that of HIF Driver and others

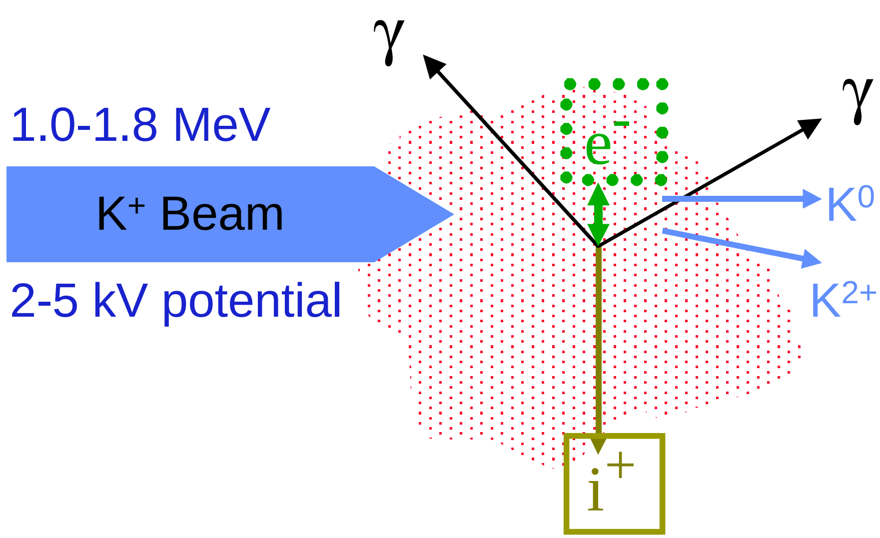
Summary/conclusions

- HIF has attractive power plant prospects, but
  - Desorption and ECE are major determinants of allowable fill factor
  - Gas desorption coefficient appears marginal for cold-bore (for wall characteristics studied), and may rule out a warm-bore approach.
- Electron emission scales with $\cos^{-1}(\theta)$ – Understood
- Gas desorption scales more slowly with angle.
- Electronic component of dE/dx is prime candidate for supplying energy to drive emission and desorption.
- Particle source for desorption not primarily adsorbed layers of gas – dust, inclusions, and oxide layers are candidates.

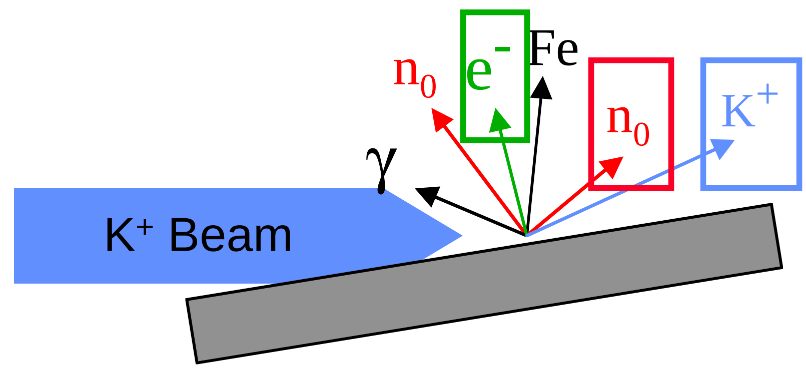
Backup material

Beam hitting gas or walls creates electrons and gas — these can multiply

Beam on gas, I_b

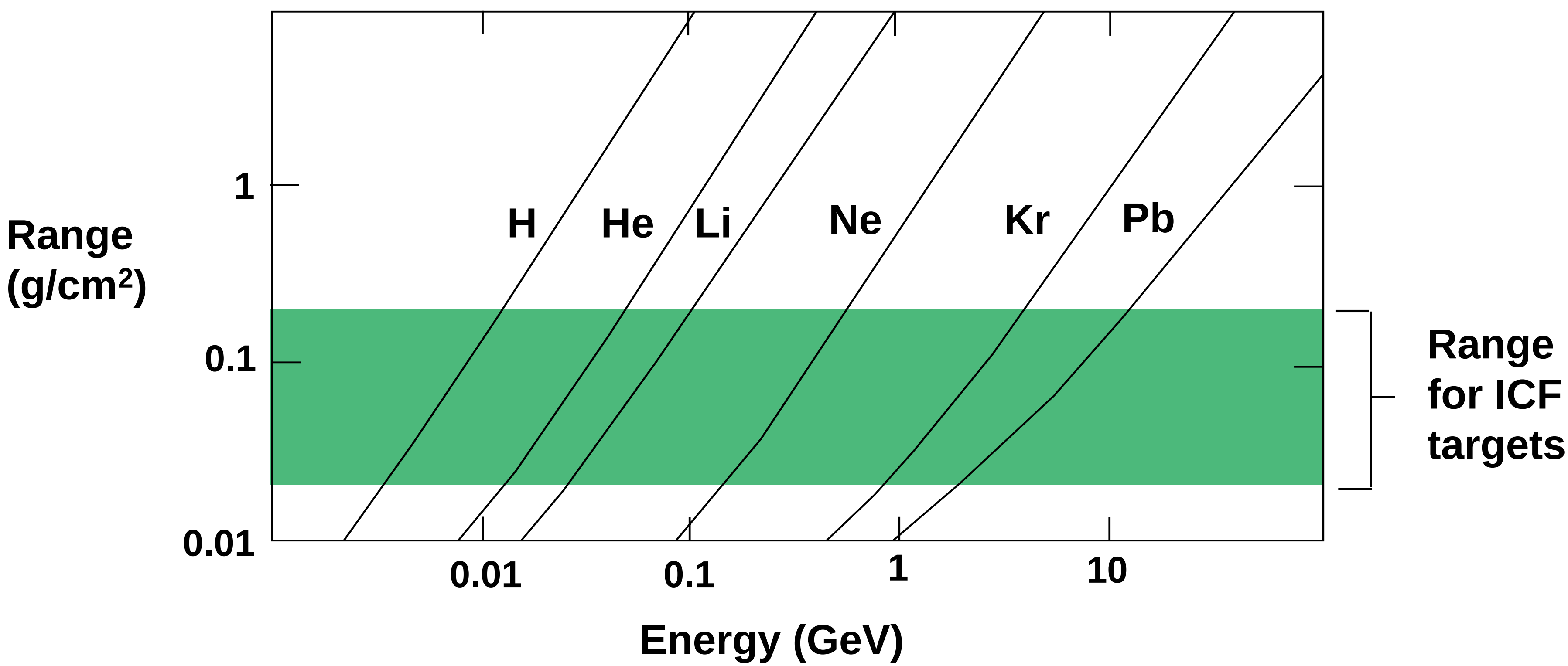


Beam loss to walls, I_{bw}



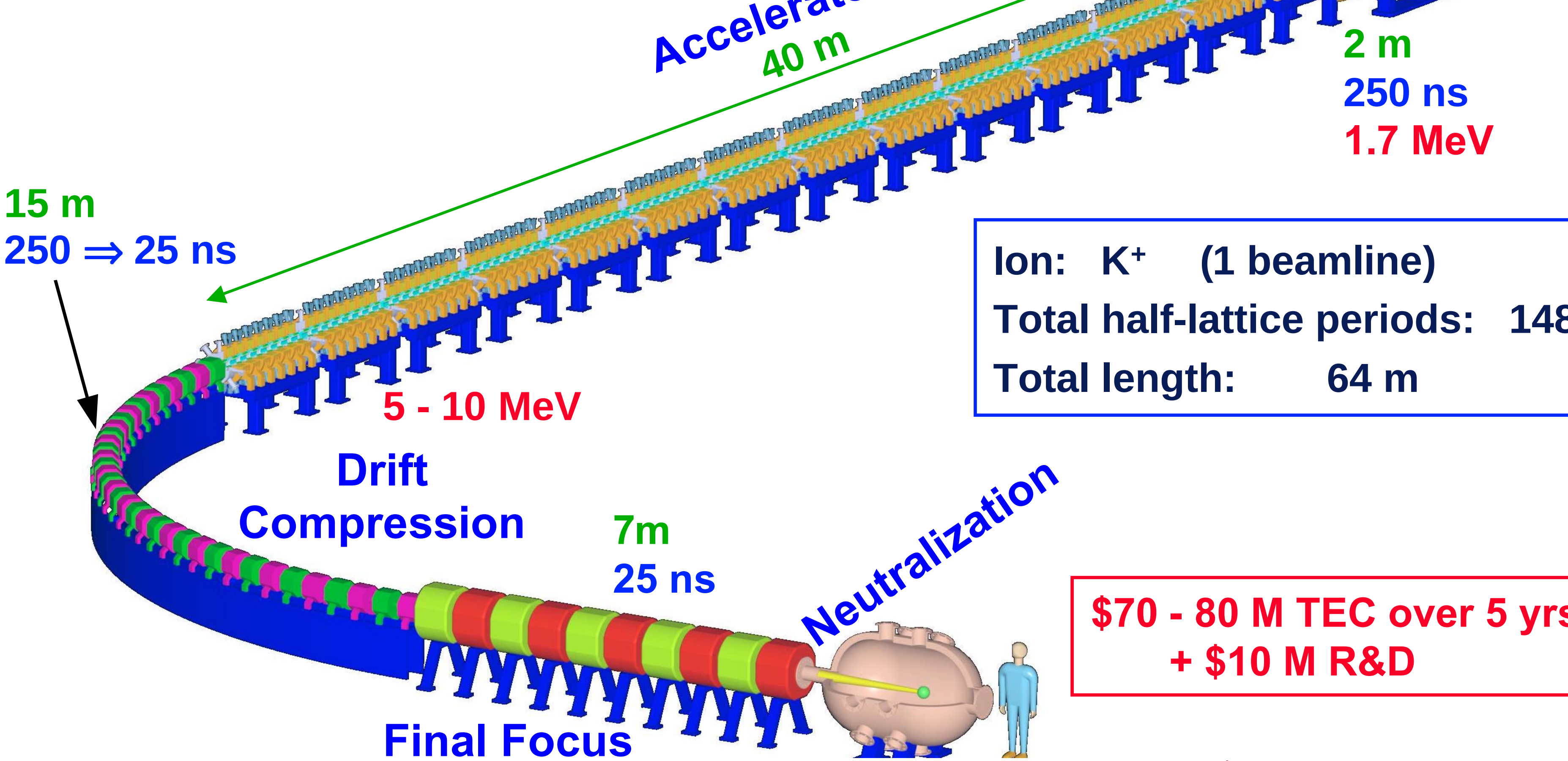
These interaction products create opportunities for diagnostics along with problems for diagnostics and beams

Heavier Ions ⇒ Higher Kinetic Energy



The IBX mission is to demonstrate integrated source-to-focus physics

Capability for pressure-rise issues
- Vary fill factor with accelerated & tilted beam
- Drift compression & final focus



Ion: K^+ (1 beamline)
Total half-lattice periods: 148
Total length: 64 m

$70 - 80 M TEC over 5 yrs
+ $10 M R&D